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FLAME SPREAD OVER SOLID FUEL IN LOW-SPEED CONCURRENT FLOW

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Introduction

This research program is concerned with the effect of low speed flow on the spreading and extinction processes of flames over solid fuels. Primary attention is given to flame propagation in concurrent flow - the more hazardous situation from the point of view of fire safety. Support for the theoretical modeling effort and ground-based experiments was awarded in 1990. In 1994, the project was awarded flight experiment definition status.

Concurrent-Flow Flame Spread Modeling with Gas-Phase Radiation

In a recent paper,[1] a model of flame spread and extinction over thin solid fuel in concurrent flow was described that uses an elliptic formulation in the leading-edge, flame-stabilization zone and includes a solid surface radiative loss. This model was used to study flame spreading characteristics and detailed flame profiles in low-speed forced flow. In addition, a flammability boundary which consists of a low-speed radiatively quenched branch and a high-speed residence-time-limited blowoff branch was established.

More recently gas-phase radiation was introduced into the flame spreading model.[2, 3] The radiation model considers gray emitting, absorbing, and non-scattering medium (CO_2 and H_2O). The equation of radiative transfer is solved numerically by the S-N discrete ordinates method. A two-dimensional S_4 (12 ordinates) scheme is adopted based on a balance of numerical accuracy and computational cost after extensive numerical testing. The major results of this model computation include:

1) Radiative heat flux is multi-dimensional in nature, and the S-N discrete ordinates method provides a net-radiative-flux vector field in the gas phase. In fig. 1, for example, the net-radiative-flux vectors are shown for a flame spreading over a thin cellulosic fuel in a 5 cm/sec concurrent flow of a mixture of 15% oxygen-85% nitrogen. To model flame spread, an accurate directional radiative flux field is needed to evaluate the radiative interaction between the gas phase and the fuel surface.

2) Using fuel properties of a thin cellulosic fuel, the radiative flux from the gas phase to the surface is always smaller than the surface emissions, as illustrated in fig. 2 (same conditions as fig. 1.) Ultimately, because the flame is optically thin, the net radiative flux from the solid surface is lost to the surroundings.

3) Gas-phase radiation losses lower the flame temperature for flames in low-speed flows, especially in the downstream flame zone. Lower temperatures shorten the reaction zone and the visible flame. The shorter flames compare better with experimental results than predictions obtained without the gas-phase radiation loss.[4]

4) Gas-phase radiation influences the behavior of concurrent flow flame spreading from the low-speed quenching limit to the high-speed blowoff limit. Figure 3 shows a comparison of flame spread rates with and without gas-phase radiation. In the low-speed limit radiative losses from the gas phase cause the quenching limit to occur at a higher flow velocity than with surface losses alone, but the high-speed blowoff limit occurs at essentially the same velocity with or without gas-phase radiation. Extinction is controlled by processes occurring in the flame-stabilization zone, where the flow first meets the flame.[5] Here the relative importance of gas-

phase radiation increases with decreasing flow velocity. At low speeds gas-phase radiation reduces the flame temperature, eventually quenching. At higher speeds gas-phase radiation is not important in this zone and flame stabilization is determined by reactant residence times. Hence, there is little difference in the two predicted blowoff limits. Flame spread rates in concurrent flow, however, depend on the integrated heat flux to the fuel over the preheating and pyrolysis zones. As pyrolysis and preheating lengths increase with flow speed, the volume of radiating species (in our case, CO_2 and H_2O) increases, amplifying the radiative feedback to the solid. The effect of increased heat transfer to the fuel overpowers the effect of radiative reductions in the flame temperature, producing a net increase in spread rate. As shown in fig. 3, for free-stream velocities above 5 cm/sec, the spread rate is higher with gas-phase radiation. Hence, unlike flame spread in opposed flows,[6, 7] where gas-phase radiation is important only at lower speeds, flames in concurrent flows can be influenced by gas-phase radiation throughout the flammable flow velocity range.

5) A U-shaped flammability map using oxygen fraction and flow velocity has been constructed for concurrent-flow flame spreading. The shape of the boundary is similar to the one determined by[1] based on surface radiative loss alone, but quantitatively the boundary is shifted because of the effects of gas-phase radiation.

6) With gas-phase radiation included in the model, steady-state flame propagation can always be achieved in low-speed flows (fig. 4). With surface radiation alone, the flame spread rate increases quickly as surface emissivity is decreased. At this time, numerical difficulty prevents us from determining if steady spread is possible for the adiabatic case.

Droptower Experiments

The first experiments on concurrent-flow flame spread over a thin solid fuel (Kimwipe tissue) were performed in 5-second droptower tests using a fuel-sample translation device.[4] In this series of experiments, direct photographs of visible flames provided the only basis for validating the numerical model. These tests showed that steady state was not obtained during the 5-second test time. While we cannot do much about the transient state of the flames in the droptower, a number of new features were subsequently added for a second set of tests to improve the procedure and the scope of data recorded:[8]

1) A new fuel-sample translation device driven by a stepping motor. This change improves the control of the sample translation speed (and the equivalent relative flow speed).

2) The camera is mounted on the translation device and follows the flame, improving the quality of the image.

3) A blinking light in the chamber illuminates the sample providing images of the pyrolysis and burnout fronts. The two-dimensionality of these features can be checked to verify the comparison to the two-dimensional model.

4) Gas-phase and surface temperatures were measured using thermocouples in several tests.

5) The performance of two ignition methods were studied: one using a serpentine heated wire and the other using a straight heated wire augmented with a nitrocellulosic doped strip.

The second test-series results show that the serpentine ignitor produces a uniform pyrolysis and burnout front while the nitrocellulosic strip produces a nonuniform pyrolysis front at ignition that evolves toward uniformity, but only in higher speed flows. The time history of pyrolysis and burnout fronts confirms the earlier conclusion that steady state is not reached in these experiments. The thermocouple (0.076mm wire) distorts the flame front for this thin fuel, because of heat loss to the thermocouple.

The temperature measurements are affected by the thermocouples' proximity to the ignition source (unavoidable since the flame spreads only a short distance in 5 seconds). Nevertheless, the temperature data are consistent with the model's predictions indicating peak measured flame temperatures in the flame stabilization zone near the solid burnout point. Measured and calculated peak temperatures are well below the adiabatic flame temperature, consistent with the predicted importance of radiative heat loss.

Glovebox Experiments

The Forced Flow Flame-Spread Test (FFFT) is a Glovebox experiment for studying concurrent-flow flame spreading being prepared for both the United States Microgravity Payload Mission (USMP-3) and the Shuttle-Mir Science Project (PRIRODA). In these space-flight experiments, the time limitation encountered in the drop-tower tests is eliminated. However, the fixed atmospheric environment in the Glovebox (cabin air) and the limited diagnostic and data acquisition capability constrain the scope of these tests. The objective of these tests will be to observe the effect of flow velocity and bulk fuel temperature on the flammability, ignition, flame growth and spreading behavior, in preparation for a more complete space-flight experiment program described below.

The FFFT flight hardware consists of a miniature low-speed wind tunnel (derived from the Wire Insulation Flammability experiment that was flown aboard the Shuttle spacelab in 1992) a control box and replaceable test samples, all shown in fig. 5. The test module provides flow control and conditioning, bulk velocity measurements, thermocouple temperature displays and optical access for photography. The front window of the module contains the temperature and anemometer displays to be included in the video images with the flames, and the window opens for replacing fuel samples.

Two types of fuel will be flown during the USMP-3 mission: flat paper samples lying in a plane parallel to the flow will be ignited in various air-flow velocities, and cylinders of cellulose formed around an electrically-heated ceramic core will be ignited at different bulk-fuel temperatures. The cylindrical geometry minimizes the mass of fuel required for heated samples and provides a simple method of uniform sample heating.

For the MIR/PRIRODA mission, four flat paper samples of different thickness will be tested. According to computed results for thermally thin fuels,[3] there is a critical fuel thickness, τ_c, above which the flame structure is independent of thickness and where spread rate varies inversely with thickness. Below τ_c, flames shrink and finally quench when the fuel becomes too thin. This series of tests is intended to validate some of these predictions.

Space Flight Experiment Hardware Definition

The proposed space flight experiment SIBAL (Solid Inflammability Boundary At Low-Speed) is intended to observe the flammability boundary and flame-spreading characteristics of thin solid fuel (paper sample) in low-speed, forced-concurrent flow. In order to determine the extinction limit efficiently, a solid fuel delivery system/wind tunnel device has been conceived that continuously feeds solid fuel to maintain the burnout location of a lengthy fuel sample (and therefore the flame) at a fixed location in the wind tunnel. The spreading flame, fixed with respect to the laboratory, will facilitate diagnostic measurements, save space, and make it possible to conduct a series of experiments quickly without changing fuel samples.

To demonstrate the feasibility of this concept, a prototype device was constructed (see fig. 6). This device is operated inside an existing apparatus providing atmospheric control, rainbow-schlieren imaging, data acquisition, and experiment control capabilities.[9] The first reduced-gravity tests of the prototype were completed in a recent NASA KC-135 low-gravity flight campaign. The solid-fuel feeding mechanism successfully maintained flames at a fixed location, indicated by the schlieren photograph, shown in fig 7., of a flame spreading over an ashless filter paper sample in a 5cm/sec flow of a 18% oxygen/82% nitrogen mixture. As is often the case in parabolic aircraft experiments at reduced gravity, the flame was disturbed by the unsteady acceleration environment (g-jitter), limiting the completeness of comparisons with the theoretical results. Nevertheless, to illustrate the type of comparison that can be made using the proposed SIBAL experiment results, fig.7 includes a contour plot of density gradients, directly related to the schlieren imagery, computed for the same conditions of 18% oxygen, 5cm/sec.

Future Plans

During the next year we will pursue several parallel efforts: 1) Continue the improvement and extension of the modelling effort including consideration of cylindrical geometry and transient calculations, 2) complete the hardware development and perform the FFFT Glovebox experiments aboard the Shuttle (USMP-3) and the MIR Space Station; 3) continue the development of prototype hardware for the SIBAL flight experiment; and 4) prepare and complete a Science Concepts Review for the SIBAL flight experiment.

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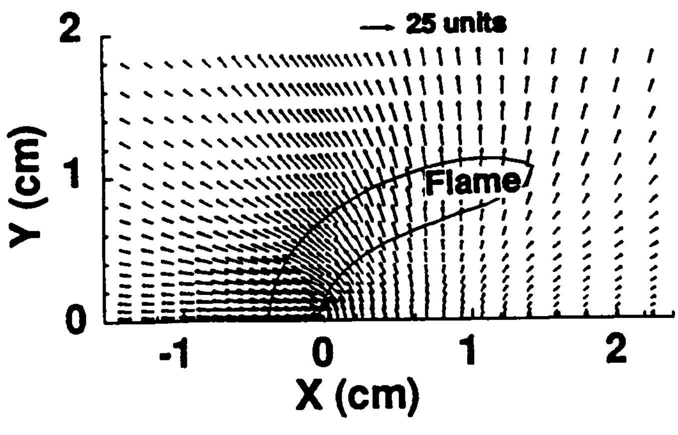

Fig. 1. Nondimensional radiative flux vectors at 15% O_2 and U_∞=5 cm/s (1 unit = σT_∞^4 = 0.011 cal/cm^2/s).

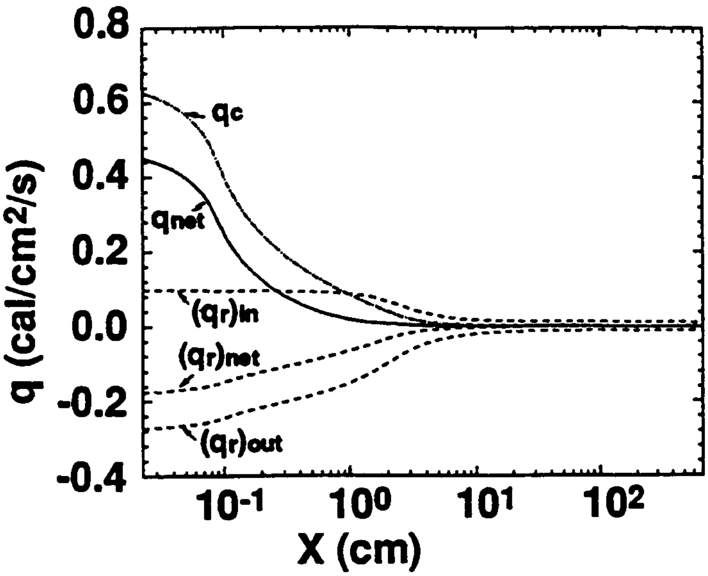

Fig. 2. Heat fluxes on the solid including conductive flux q_c, incoming gas radiative flux $(q_r)_{in}$, outgoing surface radiative flux $(q_r)_{out}$, net radiative flux $(q_r)_{net}$, and net heat flux q_{net} at 15% O_2 and U_∞=5 cm/s.

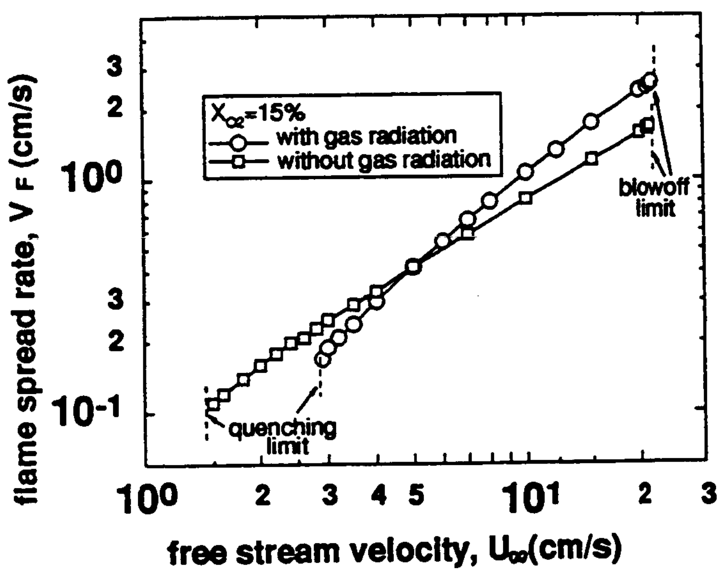

Fig. 3. The effect of gas radiation on flame spread rate at 15% O_2.

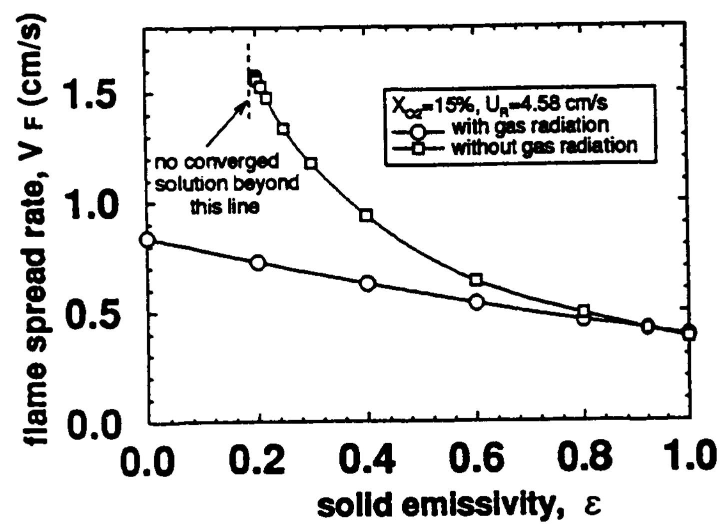

Fig. 4. The effect of solid fuel emissivity on flame spread rate for the corresponding cases with and without gas radiation at 15% O_2 and U_R=4.58 cm/s.

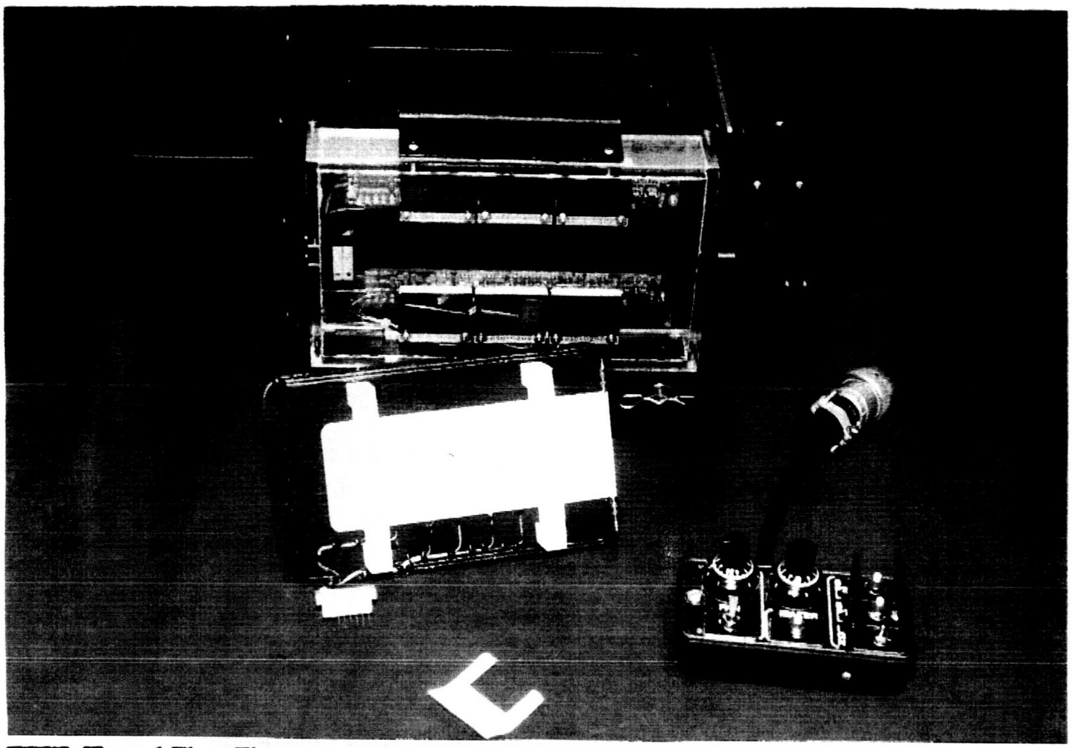

Fig. 5. FFFT (Forced Flow Flamespread Test) Glovebox Hardware

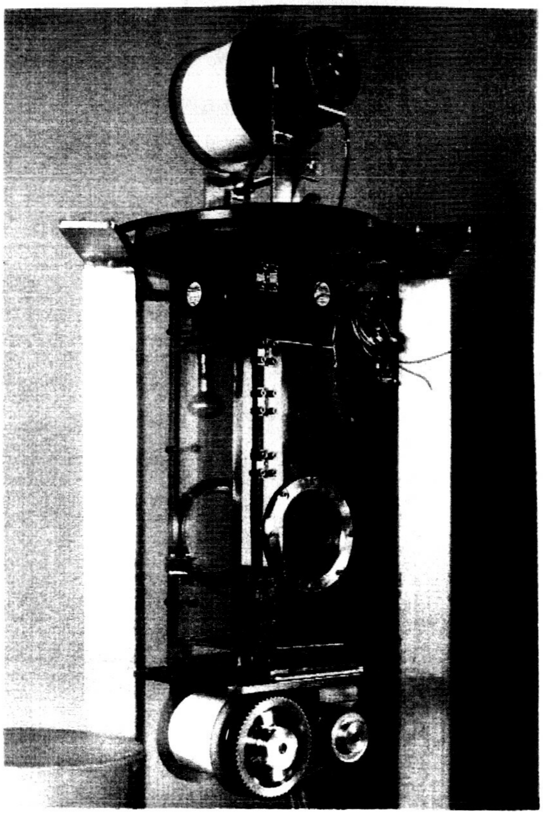

Fig. 6. Solid Fuel Delivery System prototype. Fuel advances to maintain the burnout location in the centered circular rainbow schlieren window.

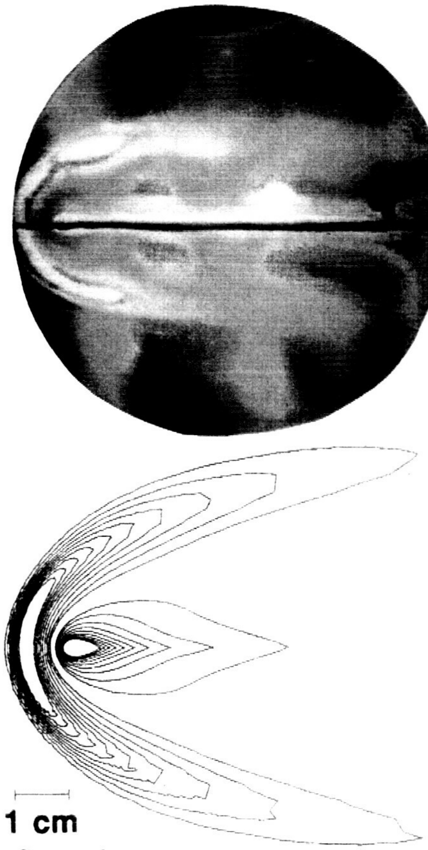

Fig. 7. Comparison of experimental rainbow schlieren image of refractive index gradients and computed contours of density gradients (18% O_2, 5 cm/s).

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